DE LA RECHERCHE À L'INDUSTRIE

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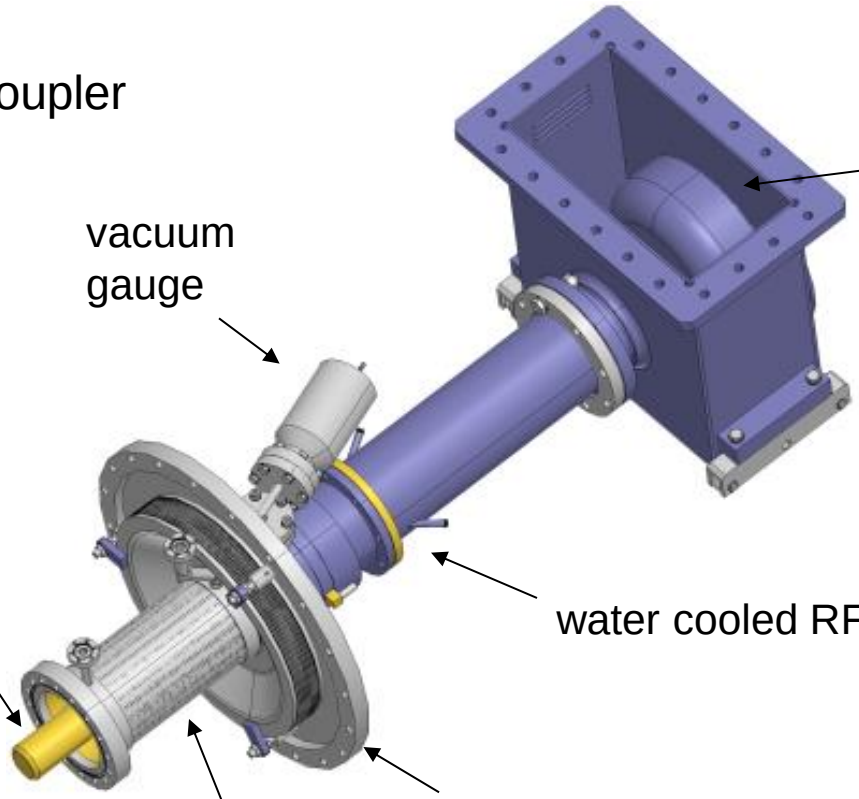
PIP-II WORKSHOP
CEA COUPLERS

G. Devanz

EU PROGRAMME CARE-HIPPI

The developpement of the 1MW 704 MHz FPC started with EU R&D programme CARE directed towards high power pulsed proton accelerators with 10% duty cycle

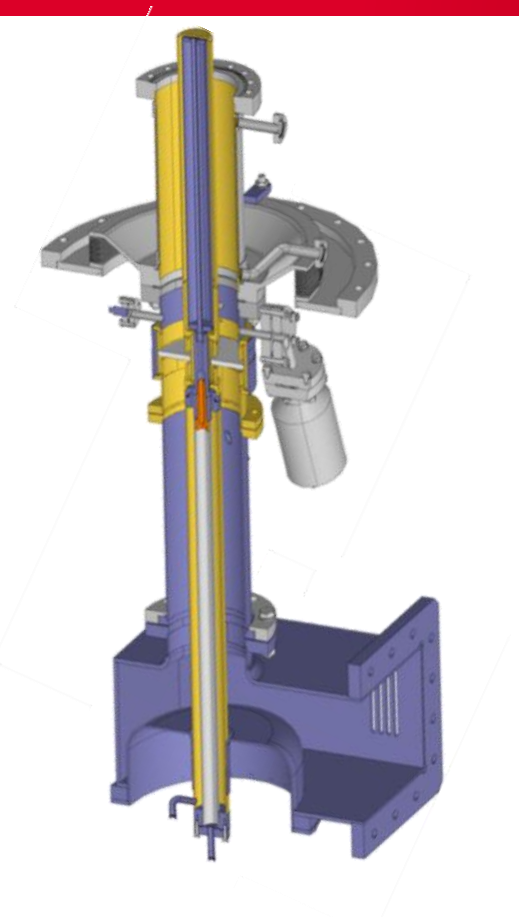
KEK-B, SNS type coupler



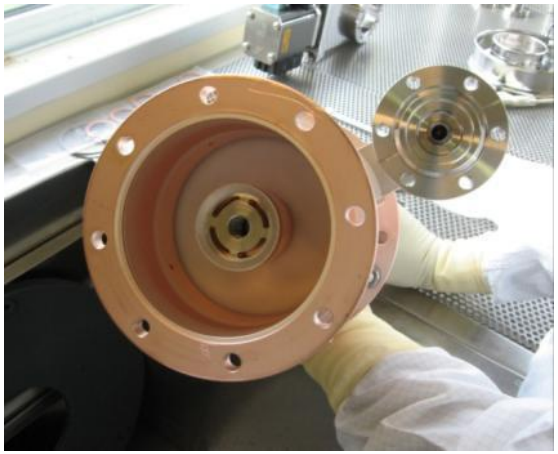
Coaxial coupler

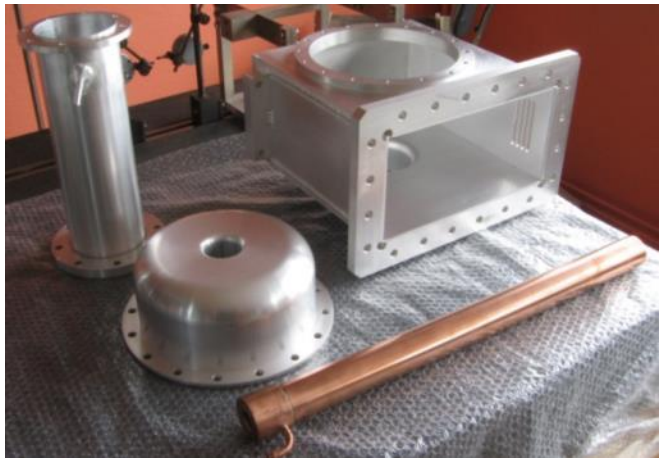
- 100 mm diameter
- 50 Ω

CARE-HIPPI FPC PROTOTYPES



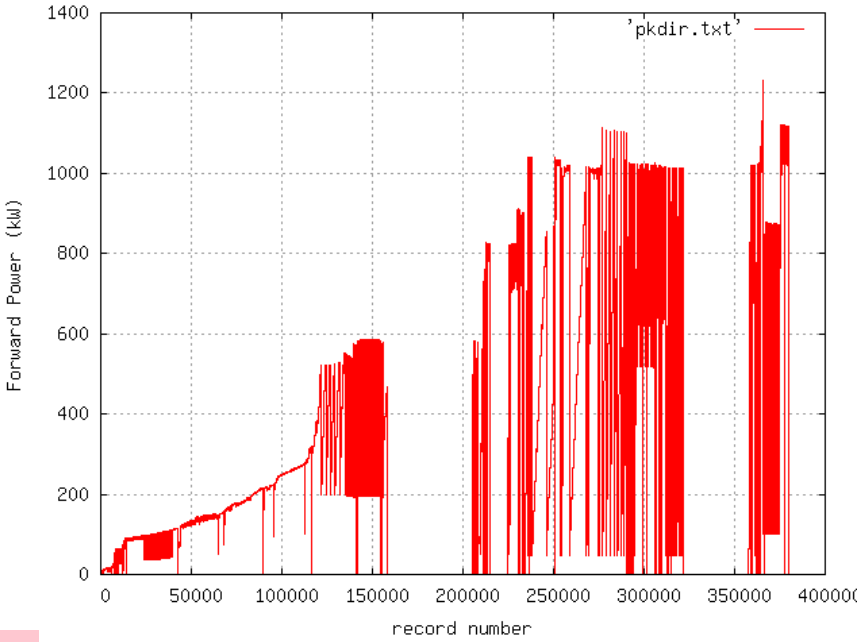
Built one pair of FPC
in industry (one for each of the 3 main compenents), except Cu film done by CERN



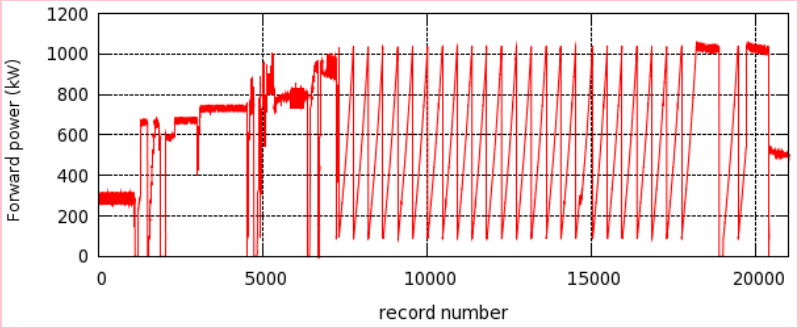


HIPPI PERFORMANCE ON TEST STANDS AND HORIZONTAL TEST CRYOMODULE

TW on conditioning test stand



Test of the HIPPI power coupler on the HIPPI cavity at 1.8 K, full reflection

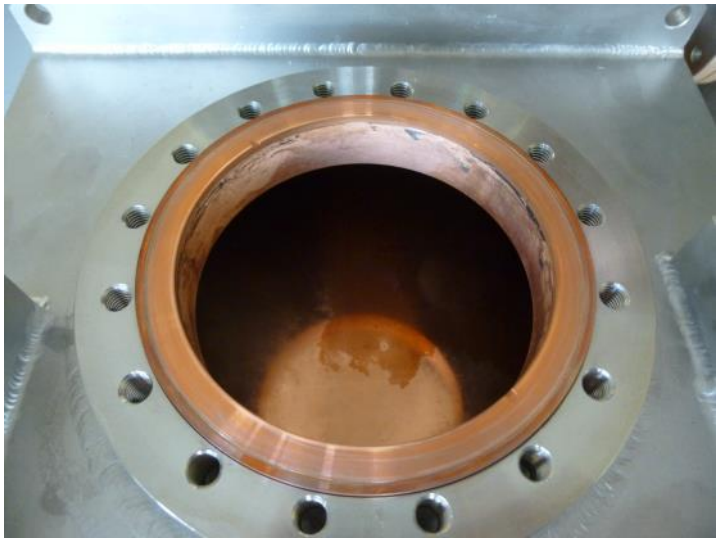


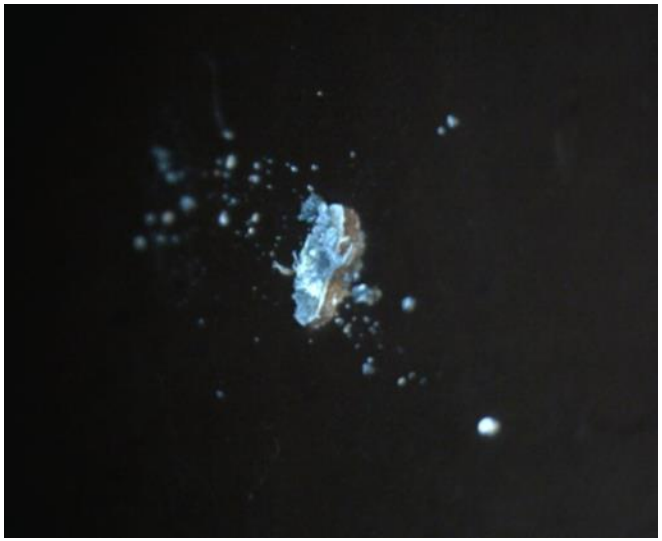
1 pair tested up to 1.2 MW, 10% duty factor
This coupler achieves 120 kW average power on test bench and on SRF cavity

HIPPI conclusion (from WWFPC-2015)

What we tested that generally cause worries :

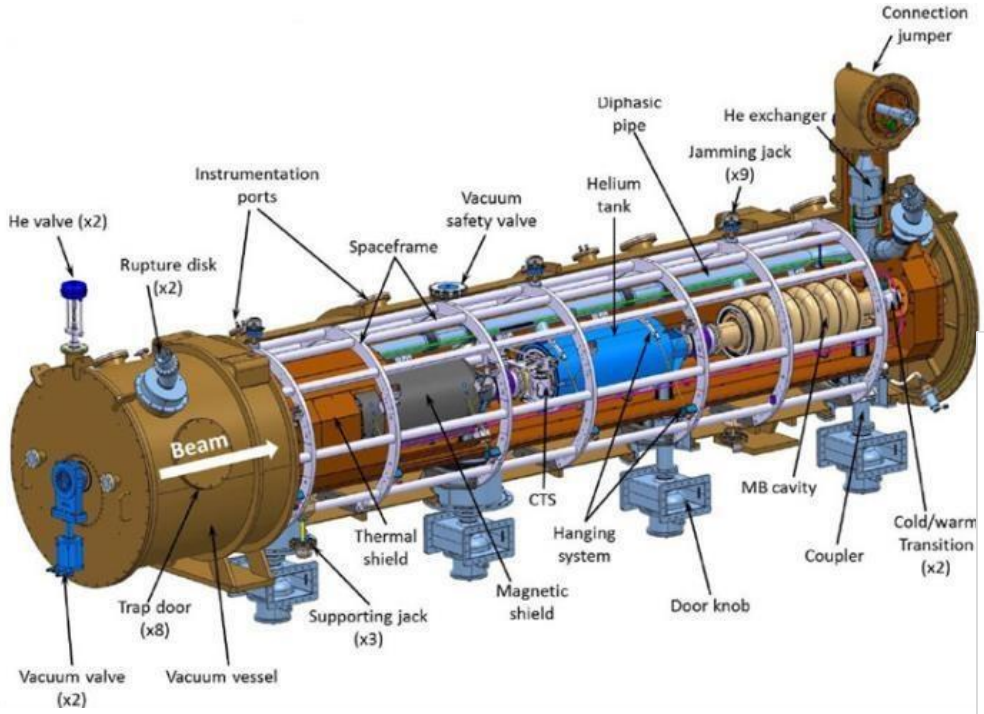
- Assembly on the cavity from the top in the clean room. No particle counting was performed in the 2009 assemblies but FE was not enhanced on the two test SRF cavities
- Massive antenna resting for years in horizontal position : no deflection observed
- More recently a new clean room test assembly of 1 HIPPI coupler was carried out in the new ISO5 clean room succesfully with particle counting
- The coupling waveguide aspect indicates it may have been the most difficult part to condition (Cu particulates were present inside)



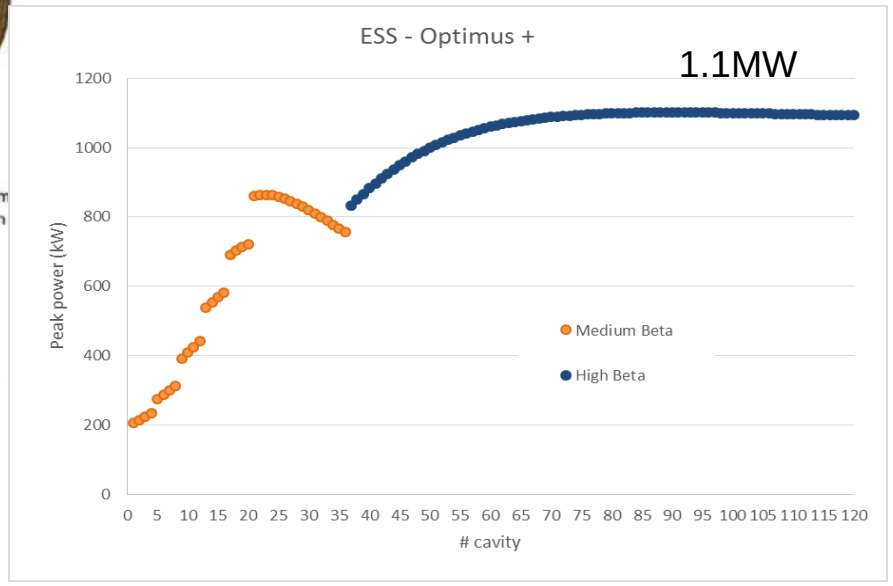


ESS ELLIPTICAL CRYOMODULES

Designed by CEA-Saclay/IRFU and CNRS/IPNO



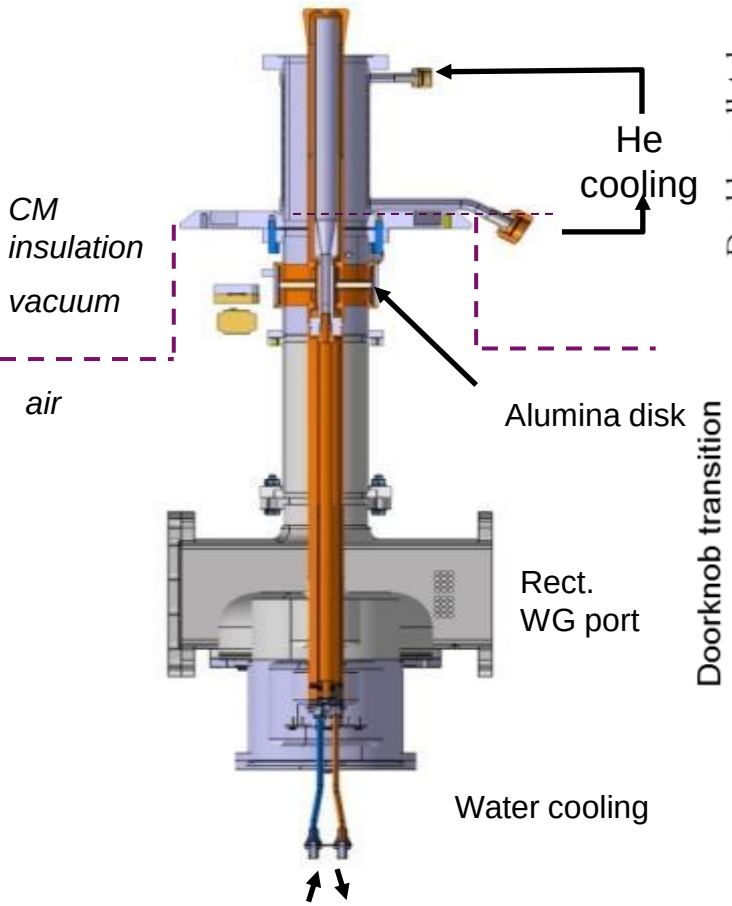
- Freq = 704.42 MHz
- **Pmax = 1.1 MW**, RF pulses at 14 Hz
- Beam pulses duration = 2.86 ms,
- minimum required RF pulse length = 3.1 ms

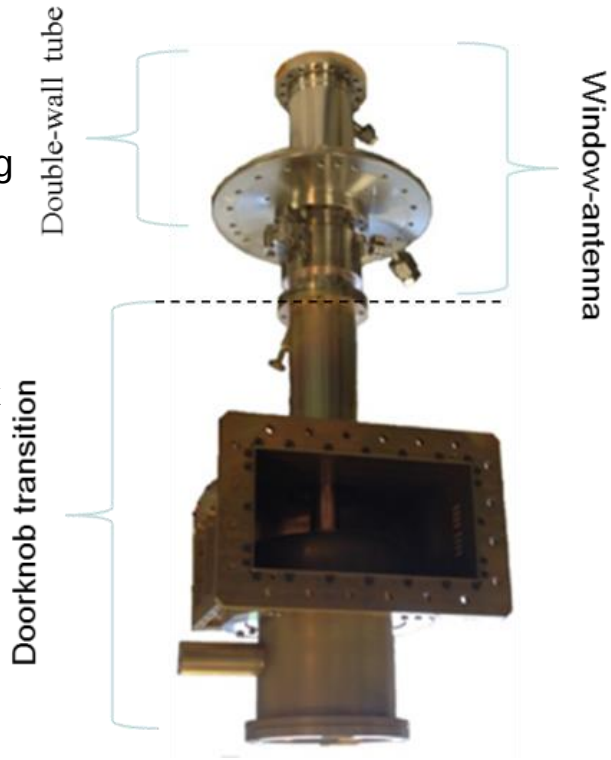


Medium and high beta differ only by the cavity length and number of cells

ESS FPC – DERIVED FROM HIPPI

- Minor changes for window and double wall tube
- New doorknob with 10 kV HV biasing capability
- Less demanding power-wise (10%DC-> 5%DC)

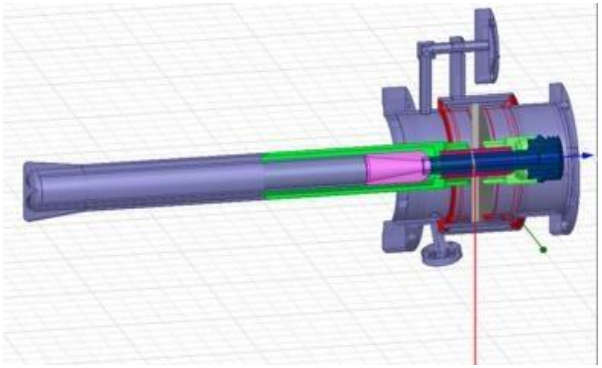




Electrical specifications

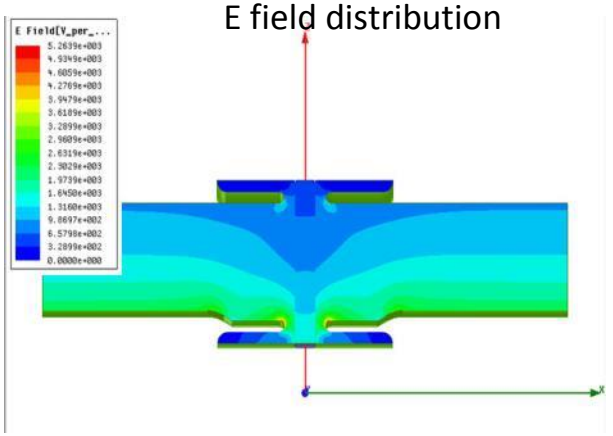
RF frequency	**704.42MHz**
Repetition frequency	14 Hz
Forward RF power	1.1 MW
RF pulse width in full reflection (all phases)	500 µs
RF pulse width in travelling waves	3.6 ms
Bias Voltage limits	±10 kV

WINDOW RF PROPERTIES

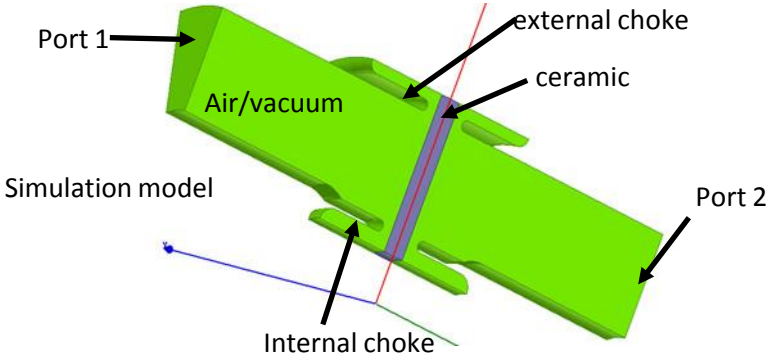


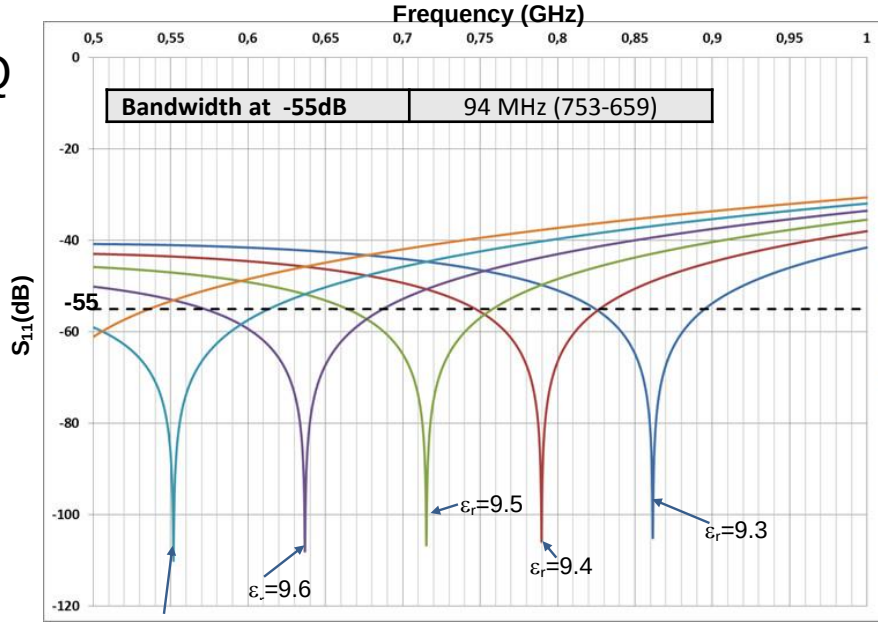
Parameters Pforward= 1.1 MW	Value
Dielectric losses (travelling wave)	10 W
Dielectric losses (full reflection)	29.4 W
RF losses for external choke (travelling wave)	1.2 W
RF losses for external choke (full reflection)	1.4 W
RF losses for internal choke (travelling wave)	6.1 W
RF losses for internal choke (full reflection)	6.8 W

E field distribution



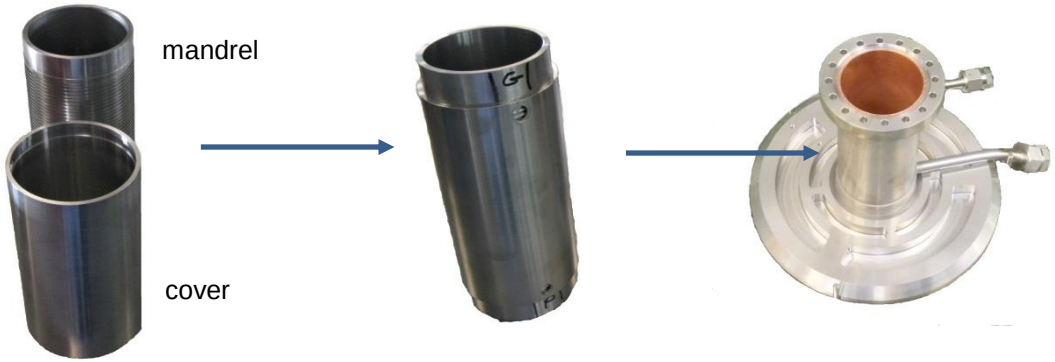
Very wide bandwidth
Same design used for 352MHz RFQ window

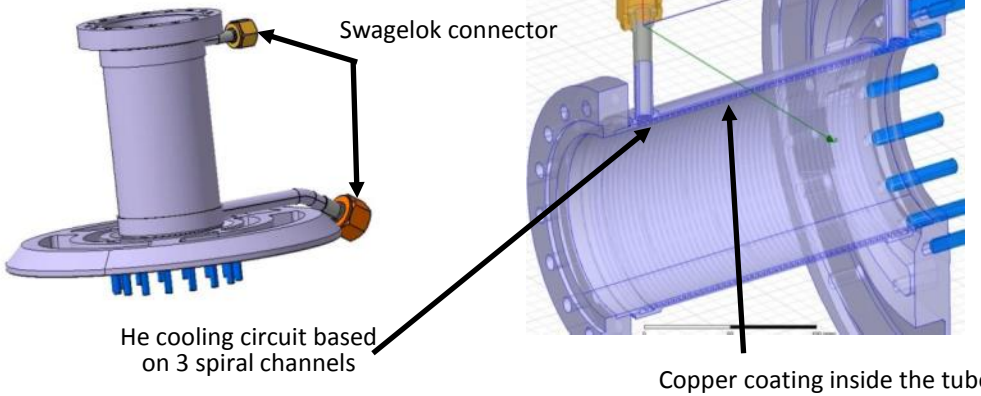


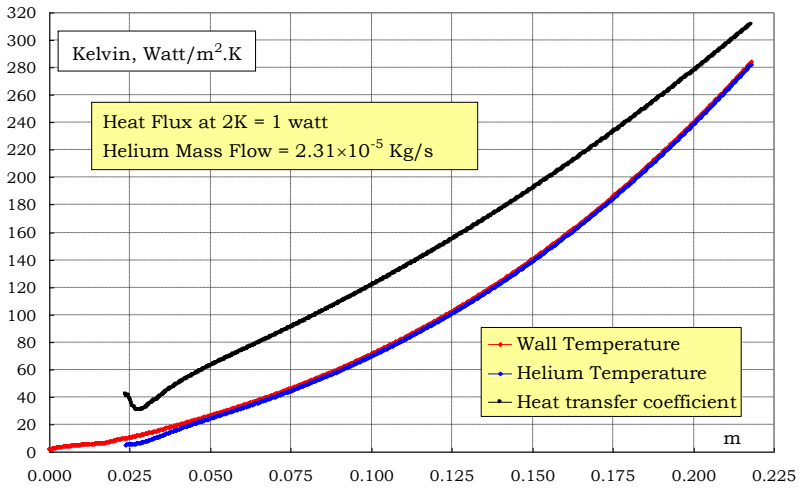


DOUBLE WALL TUBE

- Stainless steel 316L
- Cooling circuit manufactured with the shrink-fitting method
- Copper coating with 10µm(-3/+2µm) thickness and RRR∈ [20;40]



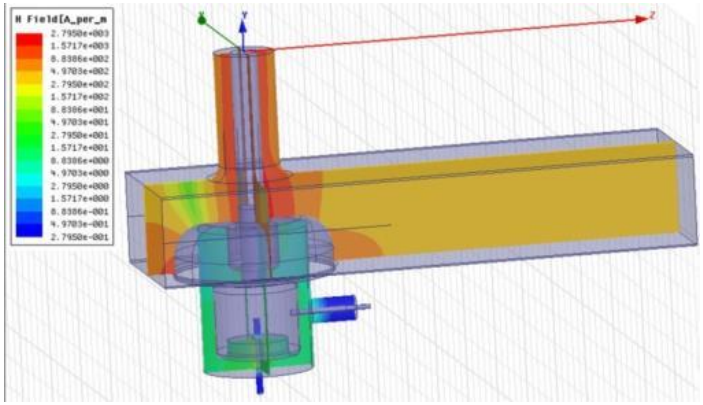


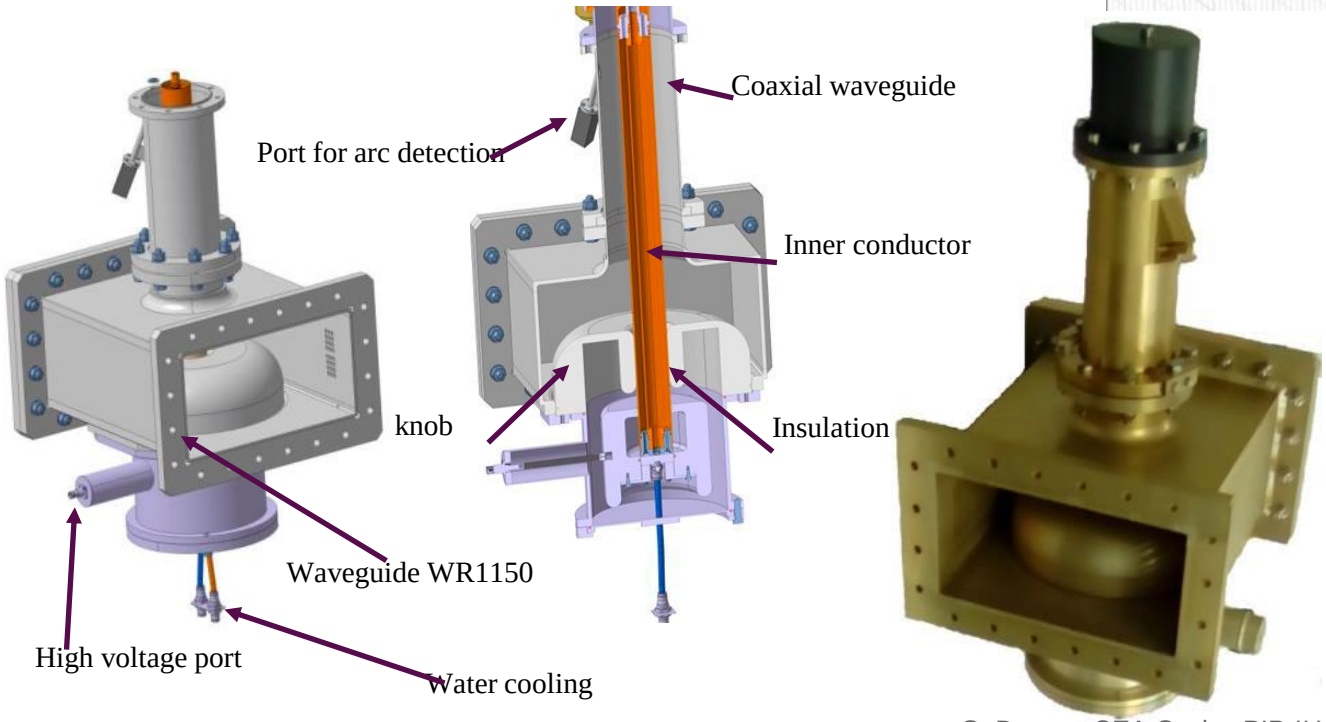


Design temperature profile

DOORKNOB TRANSITION

- PEEK Insulation able to provide 10kV insulation
- Actual measured breakdown voltage ≥18kV)

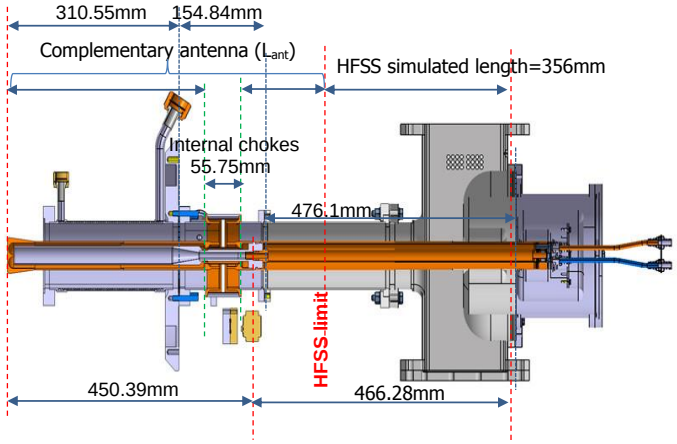




- Estimation of the power dissipated by the coupler

For 1.1 MW peak, duty cycle 5%
-RF power dissipation of the antenna:
in travelling wave 58W
in standing wave 94W
-RF power dissipation of the ceramic (tan $\delta=3\times10^{-4}$)
in travelling wave 9.3W
in standing wave 40W (worst case)

- Cooling of the antenna



Estimation of the water flow

Φ	ΔT
2 l/min	0.97°
2.5 l/min	0.78°
3 l/min	0.65°

During the conditioning: for Φ=2.4l/min

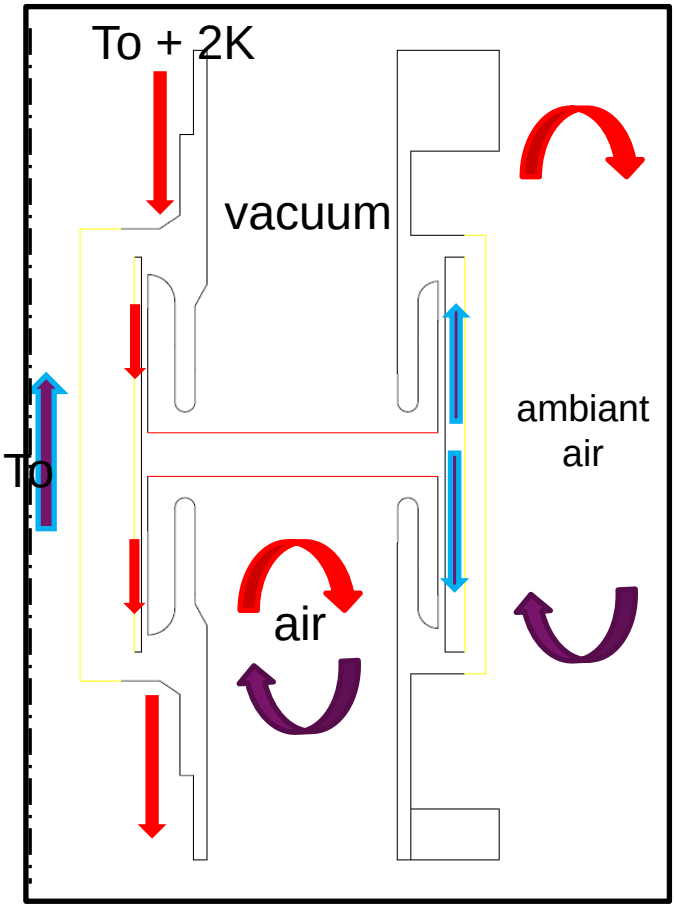
T water input=25.6°C

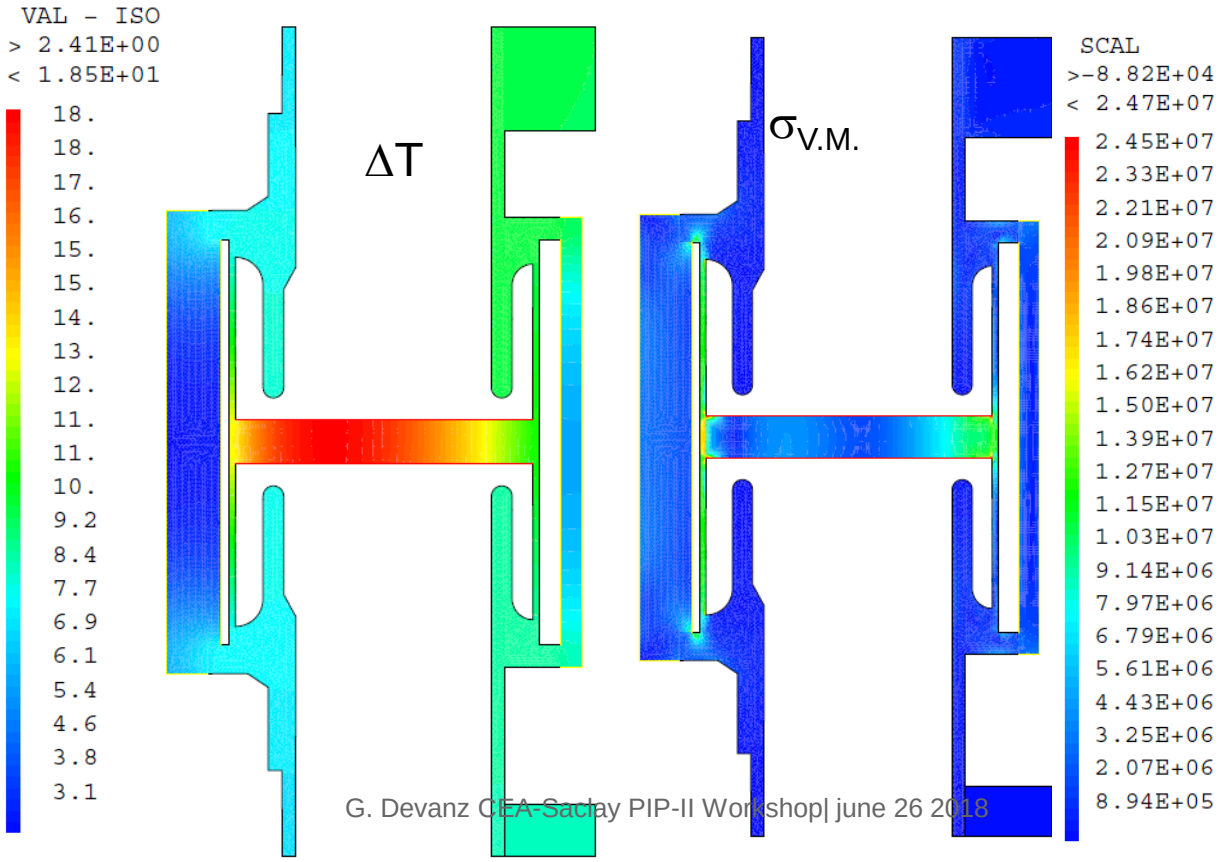
T water output=26.2°C

THERMO-MECHANICAL SIMULATIONS

- Steady state in TW 120kW avg power (HIPPI test case)
  - 2.5 x the ESS average RF power
  - pressure, convection for air and water are modeled
  - RF dissipations

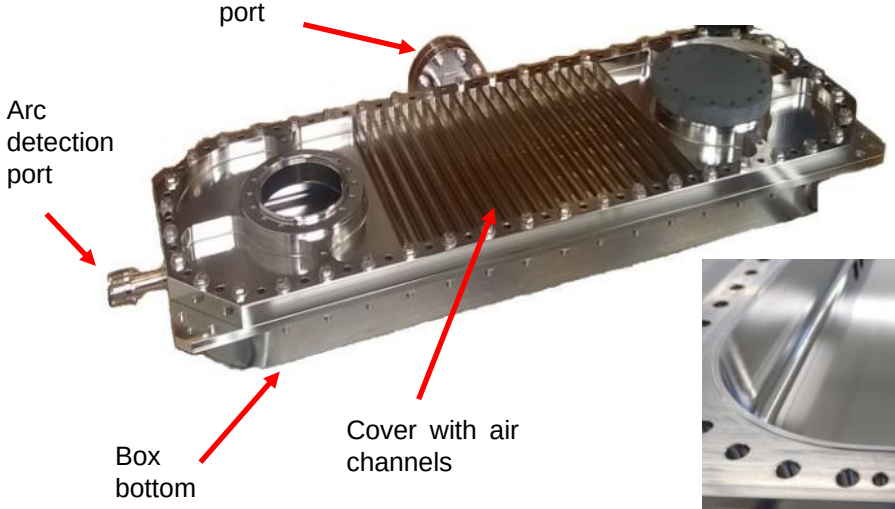
HIPPI test case	
RF PEAK POWER (MW)	1.2
Duty cycle (%)	10
Regime	TW

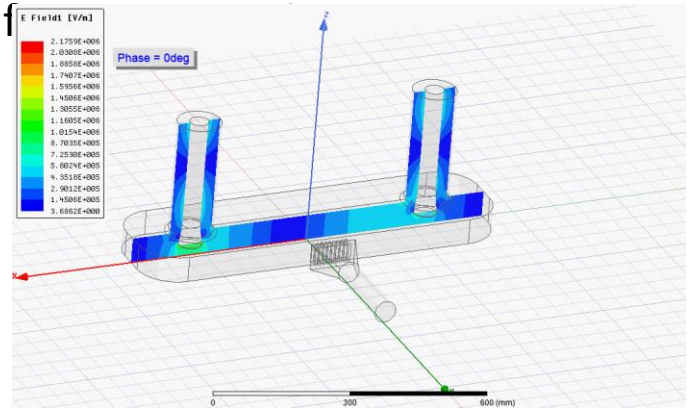




CONDITIONING CAVITY

- Lesson learned from HIPPI previous design (copper coated welded SS cavity) and E. Montesinos dismountable cavity, we tried to simplify a step further by not having any copper layer.
- Thermal design with margins showed fin heat exchangers and fan system were required.
- In use, the box was operated with good thermal stability with only air circulation on the cover plate (air channels)
- Pumping port and port for arc detection
- Aluminum wire used as seal between cover and bottom f





COUPLER CLEAN ASSEMBLY

Assembly has been performed in three different clean areas:

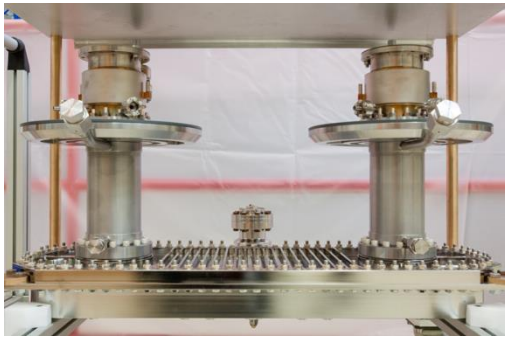
- ISO5
- ISO4
- Clean booth

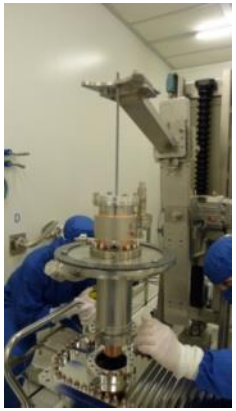
without any noticeable change in conditioning time

Top gun+Particle counter on all cavuum components

Particle free pumping and venting systems

	Double wall tube	window	Coupling Cavity
Outside of clean room	Us+tikopur	Antenna Deox T310+rinsing	Us+tikopur For new cavities/Belimed washing machine for conditioned cavities
	De-oxidation RBS T310	Ethanol cleaning of ports, outer shell	
	rinsing		
Clean room	drying		drying
	Top gun+particle counter	Top gun+particle counter	

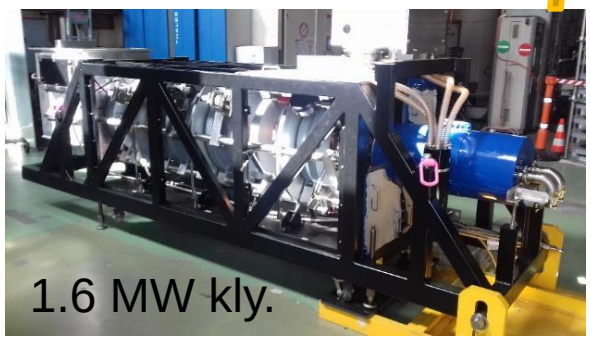


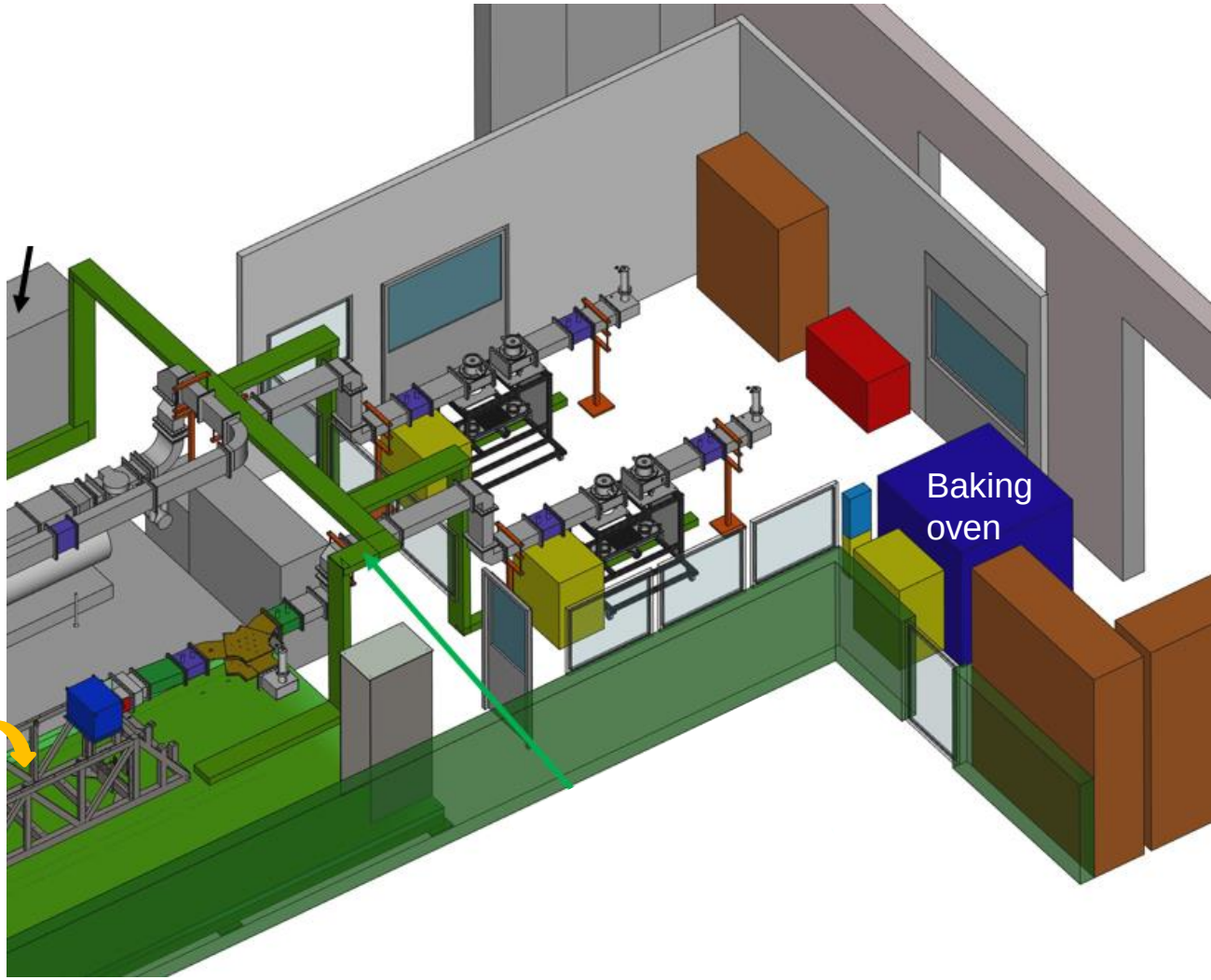


NEW CONDITIONING INFRASTRUCTURE

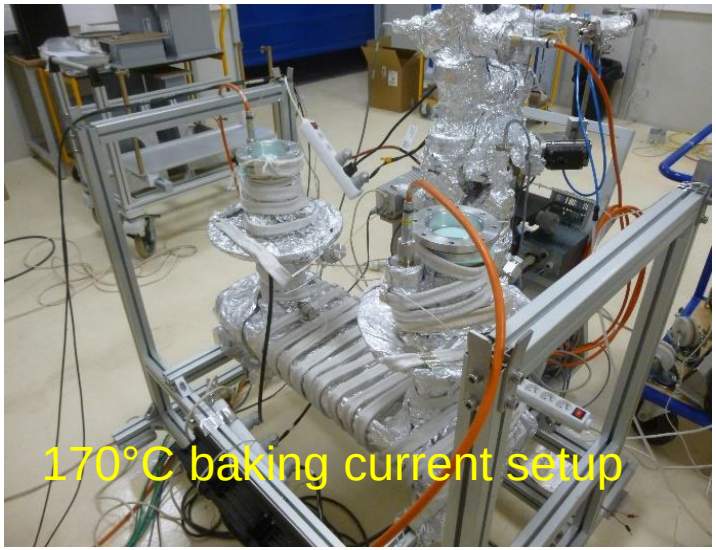
- 2 klystrons
  - existing CPI klystron + cea modulator upgraded to 1.2MW 3.6ms pulses
  - Additional 1.6 MW Thales klystron+modulator (not yet operational)

- 2 FPC pairs can be conditioned in parallel
- 2 conditioning systems w EPICS control/DAQ/ hardware interlocks
- 2 Baking ovens with N2 atmosphere



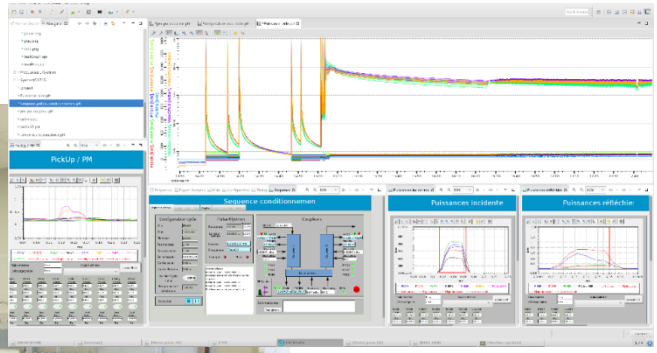


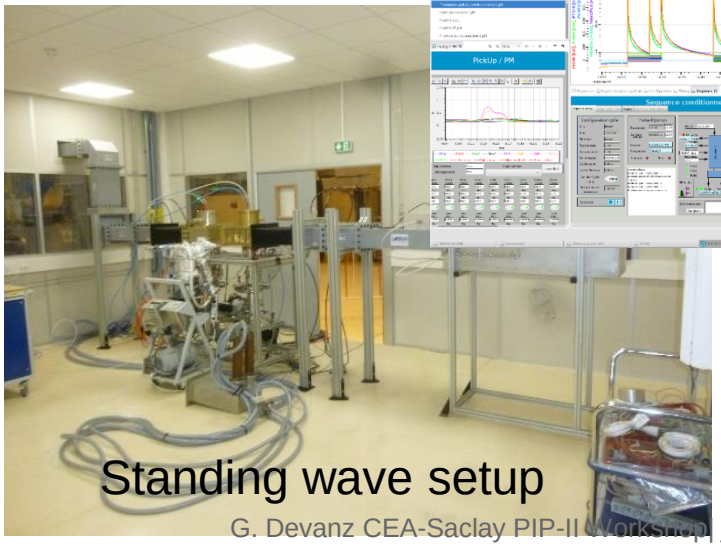
DEDICATED RF CONDITIONING AREA



New N_2 atmosphere baking oven

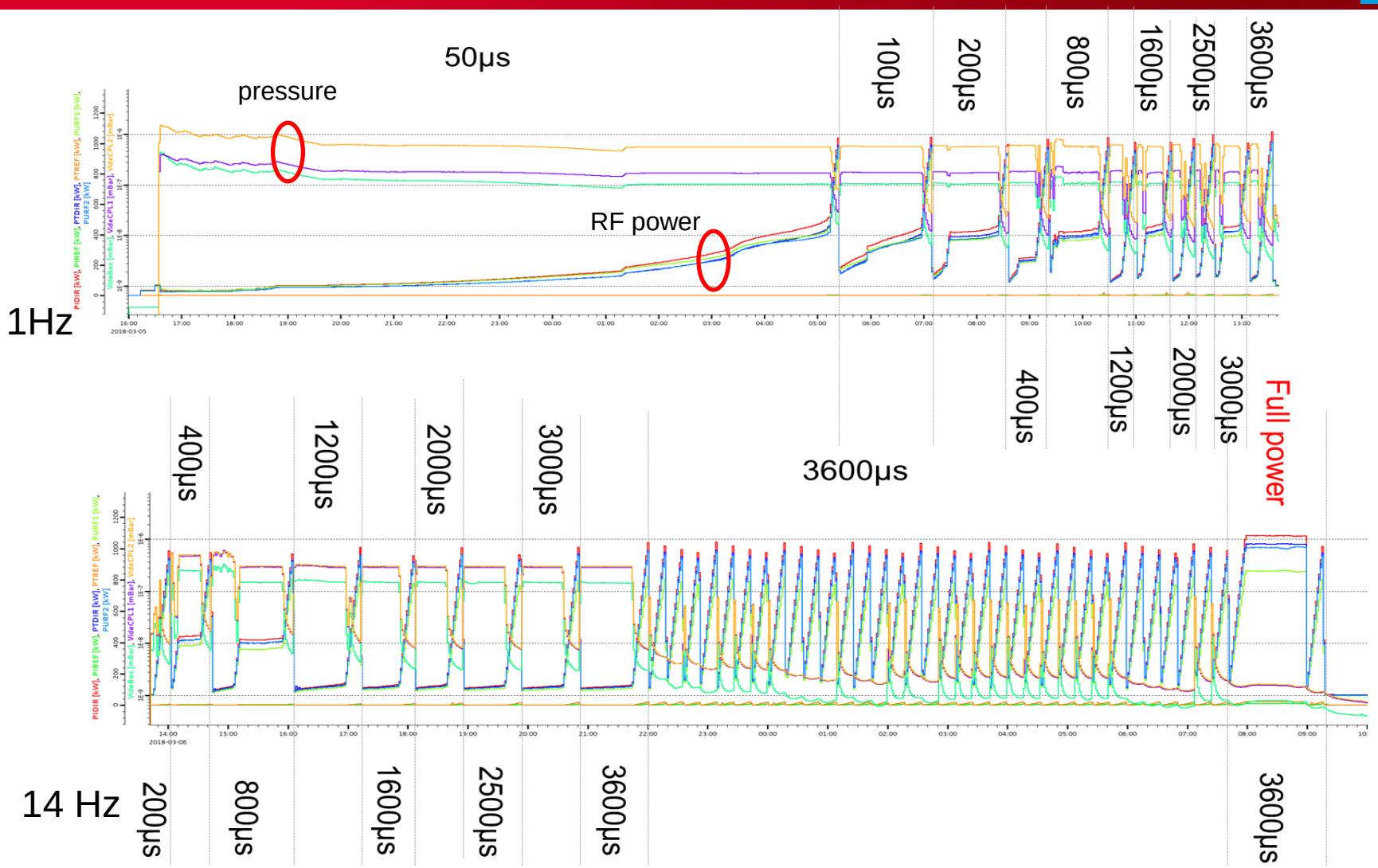
- Line1 : CPI 1.2MW klystron
- Line2 Thales 1.6 MW klystron (HVPS to be delivered)





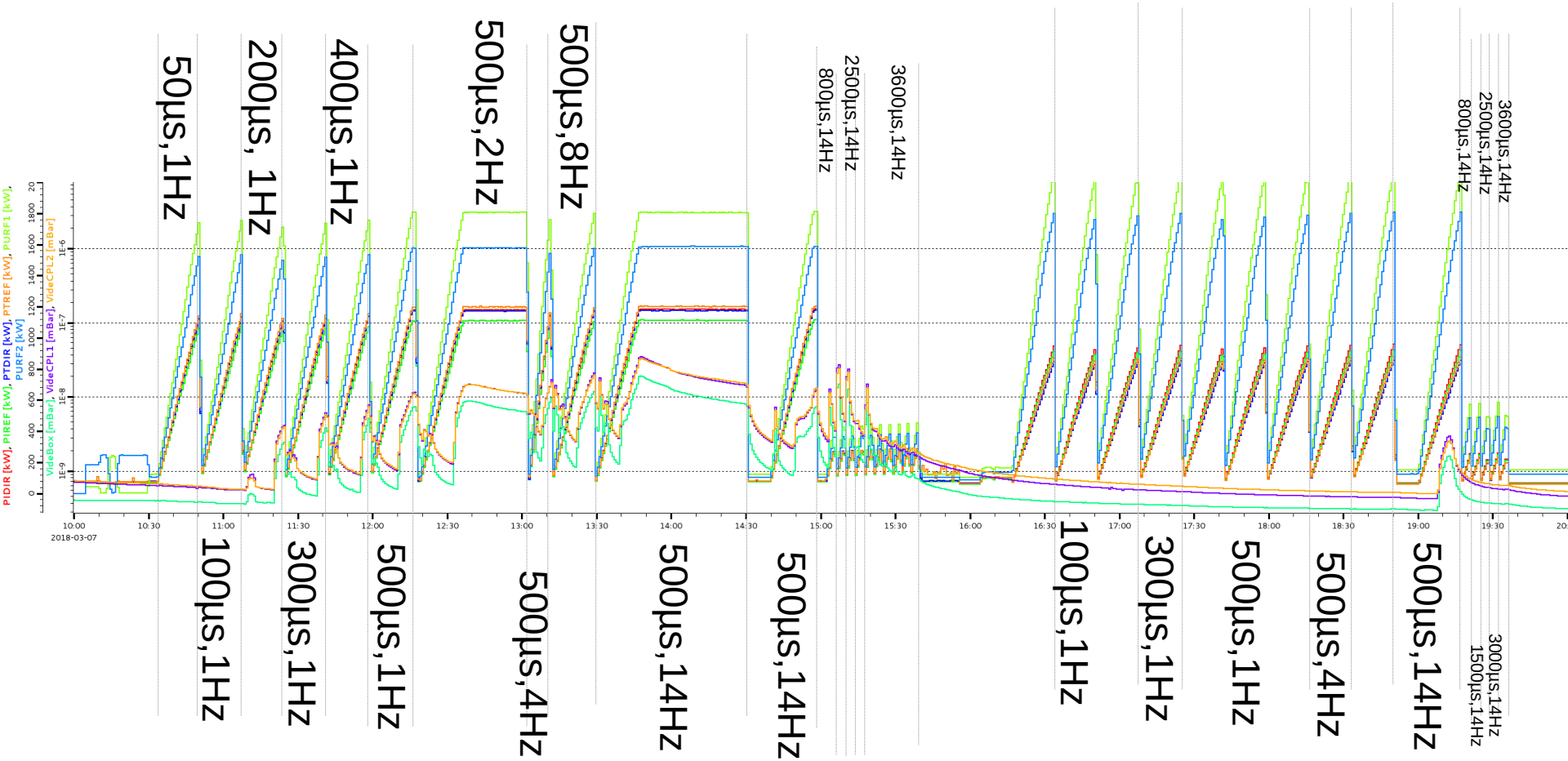
CAVITY STRING WITH PROTOTYPE FPCS

CONDITIONING SEQUENCE ::TW EXAMPLE



No bias during conditioning
Typical conditioning time 45-100hrs

CONDITIONING SEQUENCE :: STANDING WAVE EXAMPLE

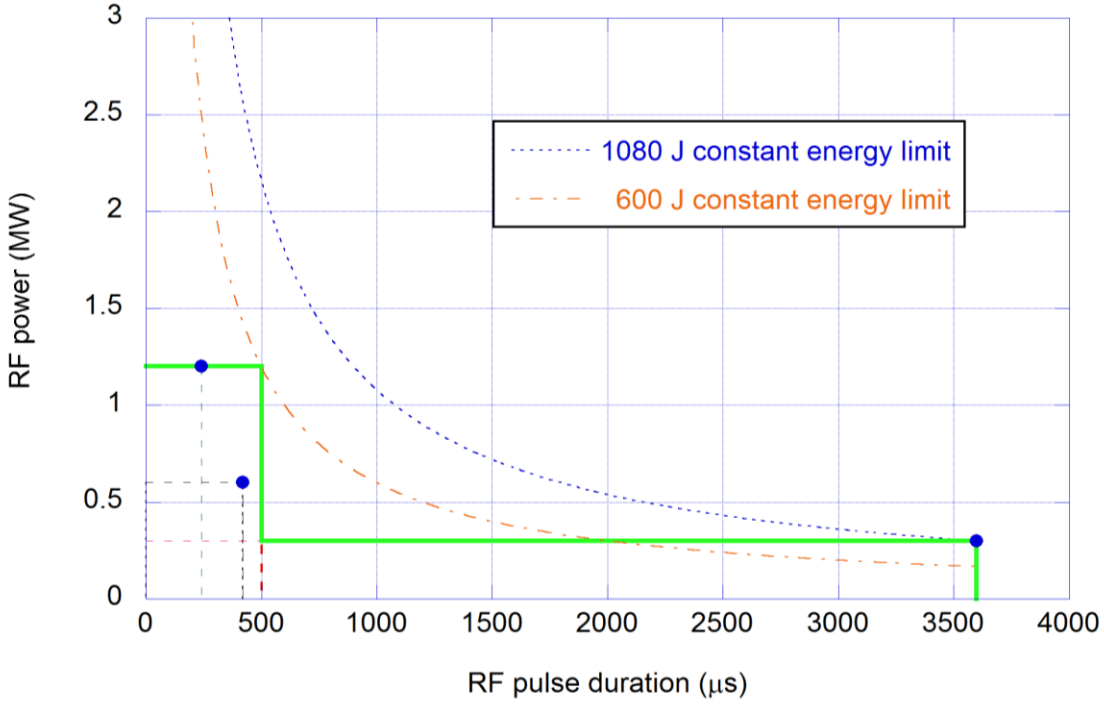


Min. E-field on both ceramics

Max. E-field on both ceramics

ESS COUPLER EXPECTED RF PERFORMANCE FOR SITE ACCEPTANCE

- Reach the peak power of 1.2 MW, 3.6 ms pulses at 14 Hz TW *in less than 120 hrs* with applied RF
- Sustained application of max. power for 1 hour
- Full reflection
  - up 1.2 MW for 500μs pulses at 14 Hz
  - Up to 300 kW for 3.6 ms pulses at 14 Hz



- 2 most arcing-prone short-circuit positions
- 4 other short circuit positions
- No time limit

MANUFACTURING PREPARATION FOR 120 UNITS

- Single vendor for 120 units
- ESS FPC Prototypes (before call for tender):
  - 8 window antenna assemblies from supplier 1
  - 4 double wall tubes from supplier 2, Cu coating subcontracted by supplier 3
  - 4 doorknob transitions from supplier 2
  - 2 complete FPCs inluding doorknob from supplier 3
- RF conditioning passed with success involving windows from 1 and 3

- Being aware of the succesful RF test of 2 pairs , 3 companies presented offers for the series (supplier 1,3 and 4)
- Two major companies involed in FPC manufacturing did not build any protoype, nor RF window:
  - One did not even participate to the first round of the CfT (publicity)
  - The other did

120 UNITS SERIES MANUFACTURING

- Initially FPC prototypes have been fabricated in a different context than the series production (FPC procurements for ESS CM prototypes)
- The series manufacturing company agrees by contract to have the coupler accepted based on high power performance
- It was not required to have them built ESS FPC prototypes beforehand in order to be part of the call for tender for the series. The bid-winning company did build a pair of prototypes
- Having a power test of the prototypes was anyway necessary to prove them the level of risk of FPC failure is acceptably low, and at least that the design (RF, thermo-mechanical) is valid
- Pres-series of 6 couplers delivered in spring 2018

SERIAL MANUFACTURING CONTRACT STRATEGY

After the production readiness review is passed,
manufacturer capability is assessed based on

- Initial Samples of each critical manufacturing step:
  - Cu coating on real size ss tube
  - Window
  - Antenna weld and electropolishing
  - Bias insulator
- a pre-series of 6 couplers : they must pass acceptance test

For each pair acceptance is based on :

- Dimension control
- Leak test, RGA
- Visual inspection
- RF performance

After preseries acceptance, and QC control audit, series production is authorized

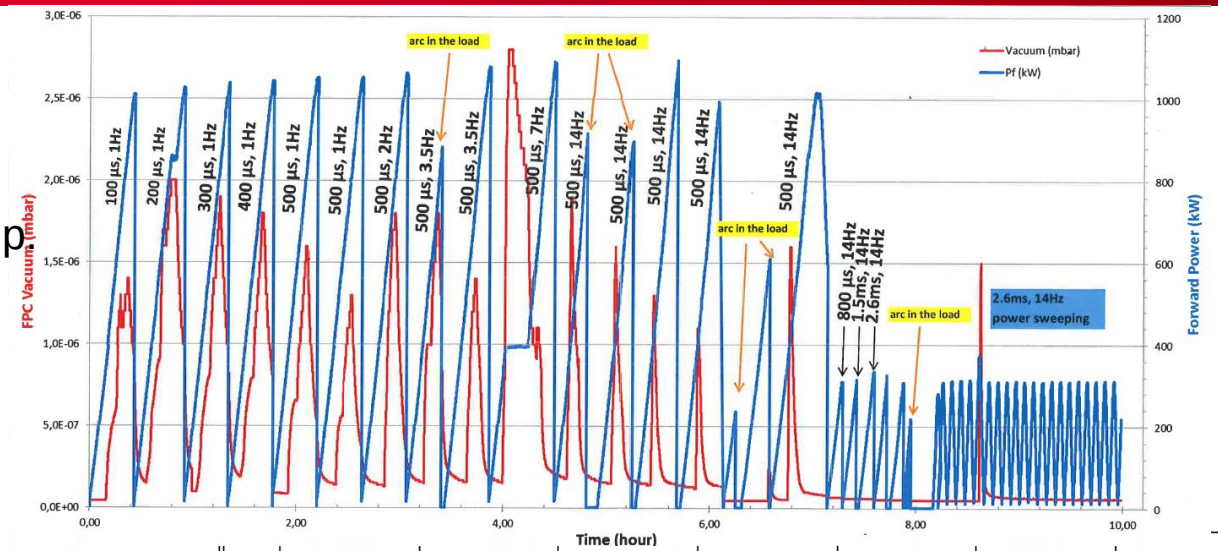
Sampling of critical processes is maintained but is set at a different rate

STATUS OF ESS COUPLERS

- 6 pre-series FPC manufactured ; currently conditioning the 2nd pair
- All but 2 existing couplers have been conditionned and part of the medium beta technology demonstrator cryomodules and acceptance of preseries
- 1 FPC has gone through installation on a ESS high beta 5-cell cavity, and installed at UPPSALA in horizontal test cryostat HNOOS; passed room temp conditioning, final conditioning with cavity at 2K, and cavity on –tune operation at 2K

COUPLER CONDITIONNING AT UPPSALA

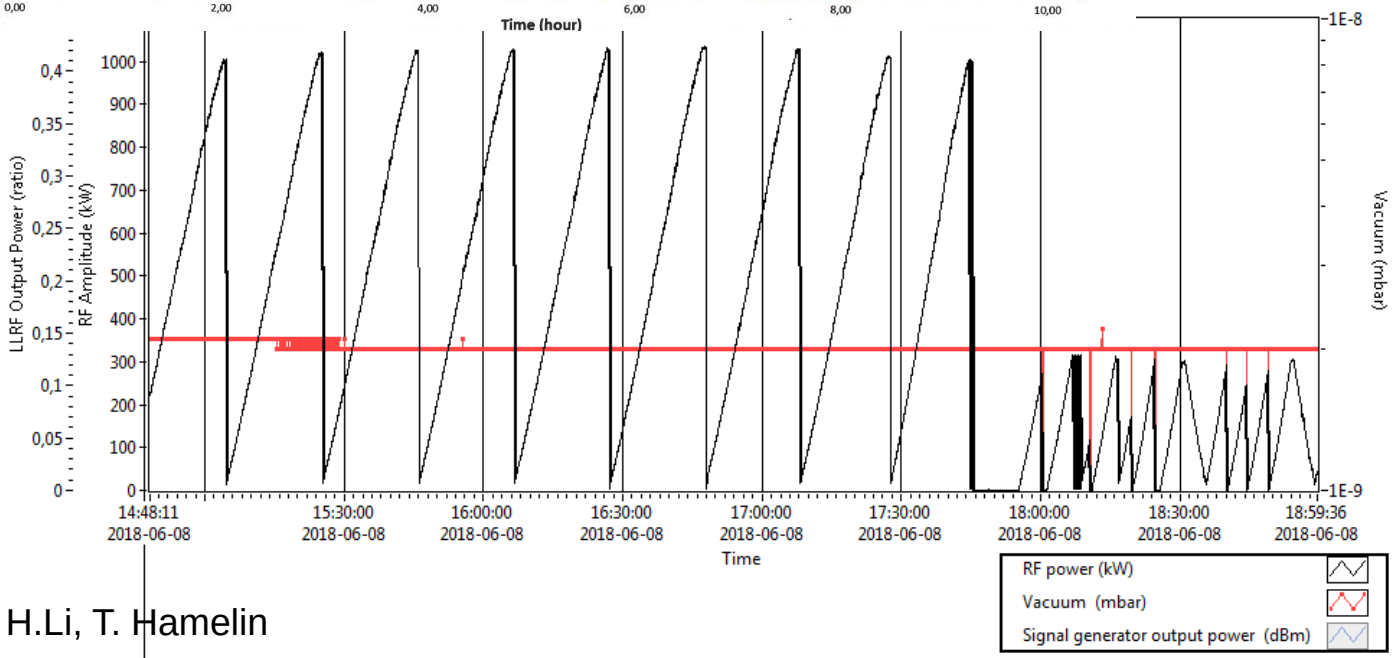
Room temp. operation



Limitations of the setup :

- Max pulse length of RF source is 2.6 ms
- Reduced pumping speed

2K operation

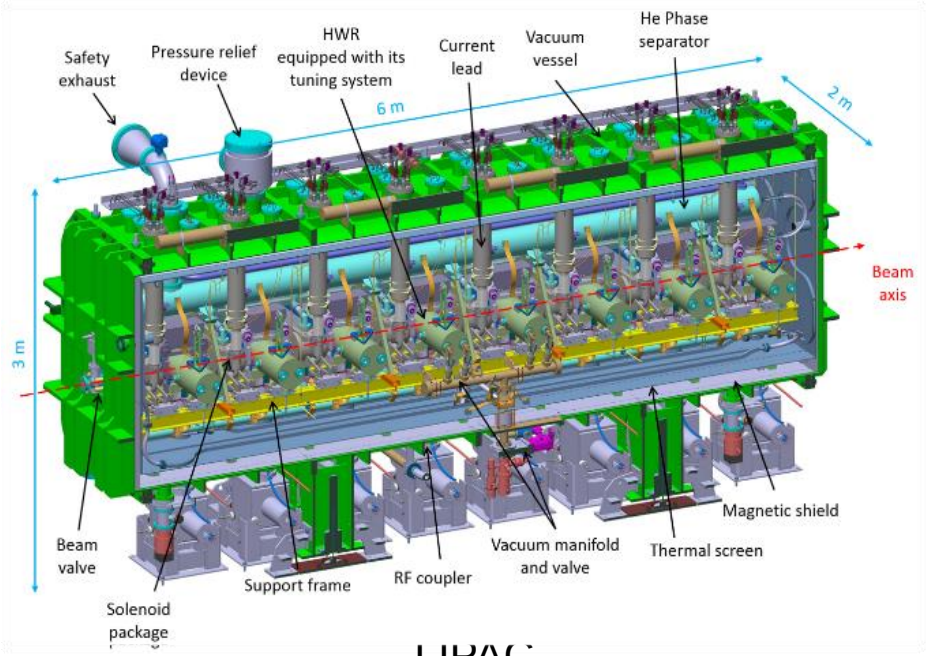


Courtesy H.Li, T. Hamelin

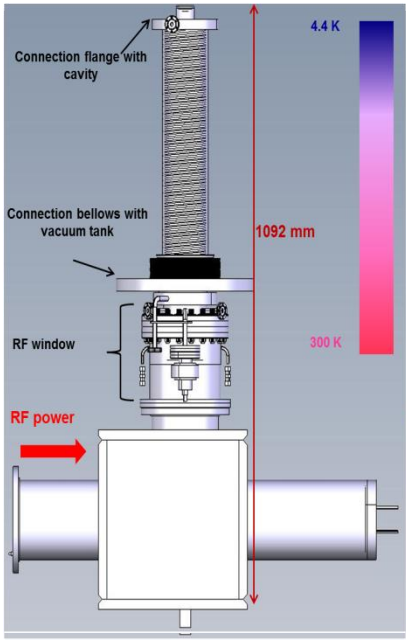
MANUFACTURING OF PROTOTYPES AND PRE-SERIES CONCERNS

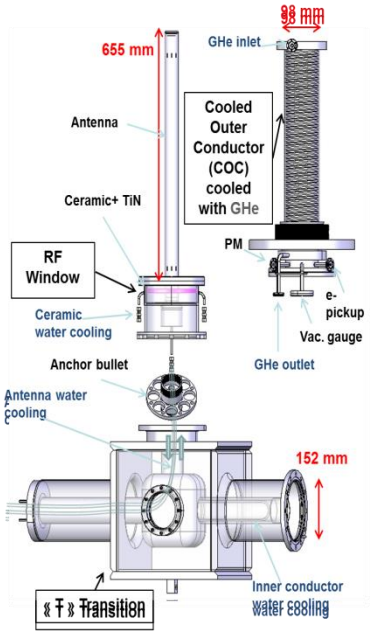
- Copper coating requires most follow-up
- In our manufacturing scheme, Cu coating is produced by a level2 sub-contractor
- At least 3 iteration on the tooling and process has been necessary in order to obtain 2+4+6 = 12 double-wall tubes with good quality.
- The coating process is operator-dependant, our experience is that each change of operator involves quality problems for the first batch this person produces.
- Doorknob Al waveguide welding repeted issues have been canceled by switching to a mechanically assembled WG

IFMIF POWER COUPLER

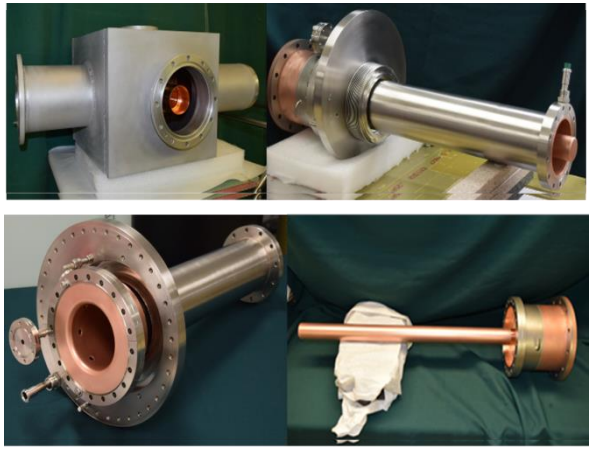


LIPAC CRYOMODULE





- **Requirement for IFMIF EVEDA phase: 8 Power Couplers** are needed with a maximum nominal operating RF power of **70 kW CW**
- **RF power validation needs for the Power Coupler: 100 kW CW in TW and SW modes**
- **Frequency 175 MHz / Qext = 6.5 10^4**



Photos of the IFMIF Series Power Coupler

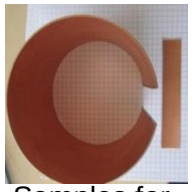
MAIN VALIDATION STAGES FOR THE PROTOTYPING PHASE

Validation of processes based on samples:

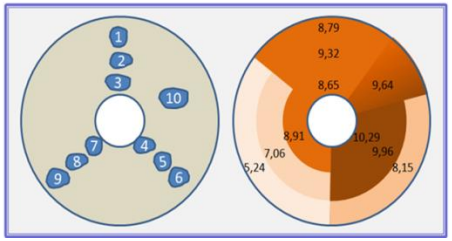
- **Copper plating validation**: RRR, thickness, adhesion
- **TiN validation**: Thickness measurements

Samples for RRR measurements

Samples for antenna plating validation



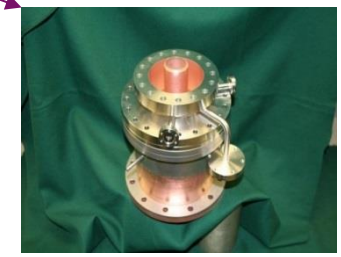
Samples for outer conductor plating validation



RBS TiN thickness measurement on vitreous carbon samples

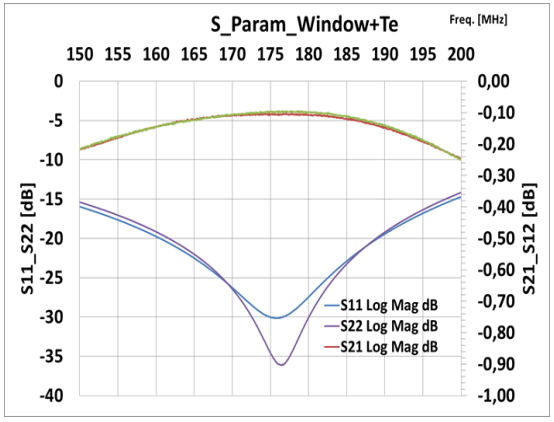
Validation based on mock-up:

- Assembling processes validation
- **RF measurements**
- **Easy cleaning of vacuum parts**



Validation based on a single prototype coupler pair:

- **Acceptance tests:**
  - ✓ Desorption test
  - ✓ Surface aspect controls
  - ✓ Dimension controls
  - ✓ Thermal shocks + Vacuum leak tests
  - ✓ Water cooling hydrostatic pressure and tightness tests
  - ✓ Assembling and disassembling test
- **RF conditioning up to 100 kW CW TW/SW**



RF conditioning test stand

CLEANING AND ASSEMBLY

- The cleaning and assembly aspects where considered since the design stage.
- Cleaning test were performed on samples and couplers parts before the final cleaning

Assembly of the series couplers

Assembly of the coupler parts in ISO5 cleanroom with adapted tools (CEA procedures)

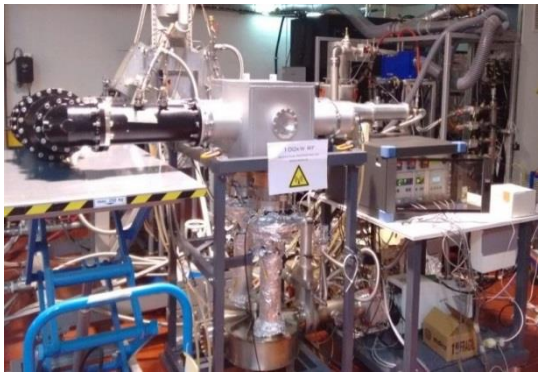
Systematic cleanliness control

Assembly of a coupler pair on their test box in ISO5 cleanroom

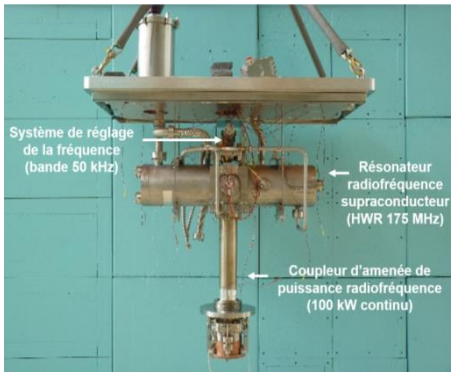
RF POWER TESTS PROGRESS

➔ **RF conditioning test operating conditions:**

- ➔ TW and SW configuration
- ➔ Several SW RF configuration allowing to have the maximum RF field on the critical parts
- ➔ Gradual increase of power
- ➔ E-current, vacuum and light detection diagnostics near the ceramic and fast hardware interlocks
- ➔ Particle free vacuum pumping and venting systems
- ➔ Efficient and hydrocarbon free pumping system



RF conditioning configuration



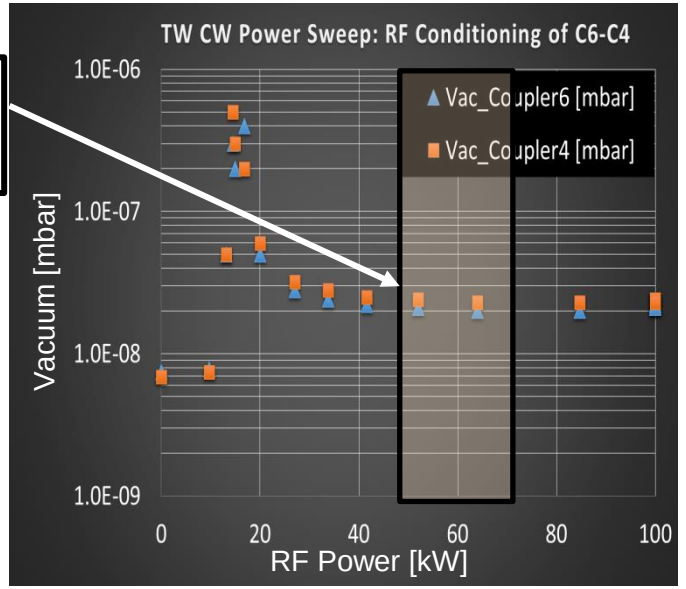
Coupler + Cavity 4.2K test

RF conditioning results:

- ➔ 2 prototype couplers RF conditioned successfully
- ➔ 1 prototype coupler RF tested successfully on HWR cavity.
- ➔ 4 series couplers RF conditioned successfully
- ➔ 4 series couplers cleaned and assembled to be tested soon

The RF conditioning procedure allowed to have a low degassing of the surfaces (<10^{-7} mbar) at the operation power and even at 100 kW CW and TW and SW configurations.

Couplers Operation Power Range



IFMIF MANUFACTURING PHASE ISSUES

- Several years hiatus between protyping and series manufacturing, covered within a single contract with the same manufacturer
- Copper coating quality issues, requiring stripping of layer and re-process for most of parts
- company did not provide the top level QC due to the low number (8) of couplers
- Repeated cleanliness issues, dimension control issues

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